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A NEUTRINO COMMUNICATIONS SYSTEM,(U)
APR 78 J ALBERS, P KOTZER N00014-77-C-0363

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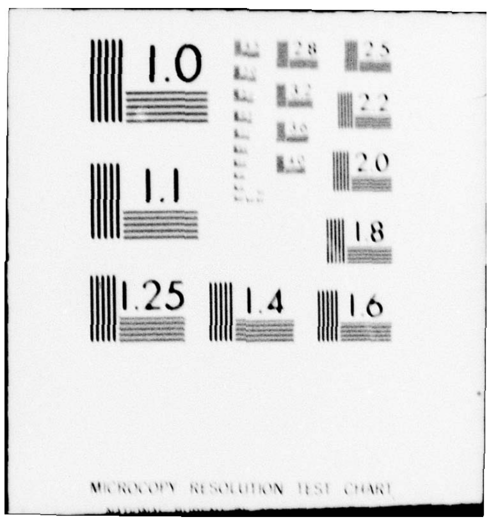
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MICROCOPY RESOLUTION TEST CHART

25 APRIL 1978

(6) A NEUTRINO COMMUNICATIONS SYSTEM

Contract N00014-77-C-0363 new

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ABSTRACT

Described in this note are modifications to the Fermilab Accelerator loading and unloading system, a time synchronization system (to provide the necessary common time base) and a (as described in Fermilab proposal 561) receiver which serve as a theoretical model for a workable neutrino communications system. The communications system is based on the fact that protons circulate in thirteen booster batches each consisting of 84 precisely spaced rf buckets** each bucket one nanosecond wide and 18.83 nanoseconds in spacing. An encoder is proposed to write the information in digital form.

TEXT

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Proposal 561 to the Fermilab (1) early in 1977 describes an experiment which would be capable of detecting neutrinos produced at the Fermilab Accelerator near Chicago in a deep ocean site in the North Pacific Ocean area. Here, we describe in detail how the proposed experiment can be used to demonstrate the feasibility of an interesting and novel neutrino communications system.

*Supported by the Office of Naval Research.

**The concept of a bucket was first believed to be used by K. R. Symon and A. Sessler (Proceedings of CERN accelerator conference "1956") and later by Donald Kerst in a proposal for an electron/positron colliding beam experiment.

Beam Fine Structure

Three radio frequency accelerating systems at the Fermilab serve to induce "fine" structure in an otherwise continuous proton beam. The rf structures of the linac, the booster and the main ring is schematically depicted in Figures 1a, 1b and 1c below. To review, the FNAL linac utilizes a 200 MHz radio-frequency (rf) system to accelerate the hydrogen ions from a few to 200 MEV. This system bunches the protons into bins 0.14 ns wide 5 nanoseconds spacing. On the average it takes about 3 linac bins (which unfortunately become smeared out) in the booster ring to "bunch" into one booster bucket.

The 30 MHz rf accelerating system of the booster increases to 52.8 MHz as the protons are accelerated to 8 GeV bunching the protons into 84 circulating buckets each about one (1) nanoseconds wide and thirty-three (33) nanoseconds in spacing. Then the booster beam is synchronously transferred into the main ring at 52.8 MHz where it is gradually increased to 53.1 MHz when protons reach the design energy of 400 GeV. Thirteen (13) booster batches, each consisting of 84 buckets, are used to fill up the main ring, leaving 1113 - 1092 = 21 buckets empty. The 53.1 MHz rf of the accelerating system in the main ring bunches the protons into one ns wide buckets with 18 ns equal spacing.

After acceleration to desired energy, the protons are extracted then guided along by a series of magnets which effectively aim the beam in the direction of the neutrino interaction receiver located at large terrestrial distances from the neutrino source.

Two possible classes of neutrinos, prompt and delayed, can be used in the communications system. The prompt neutrinos, not yet confirmed by experiment, need no decay tunnel. These neutrinos are assumed to be associated with the heavy leptons observed by Martin Perl at Stanford. The ν_τ neutrinos would arise from sequences such as:

$$p + Al \rightarrow \tau^+ + \tau^- + \text{hadronic shower}$$

$$\tau^+ \rightarrow \bar{\nu}_\tau + \mu^+ + \nu$$

$$\tau^- \rightarrow \nu_\tau + \mu^- + \bar{\nu}_\mu$$

The "delayed" neutrinos are decay products of well known particles such as the pi and K mesons produced when the buckets of protons strike the aluminum target. By focusing the pi and K secondaries and allowing them to decay in a long tunnel, intense beams of mu neutrinos which retain the memory of their indexed bucket are produced which will pass through the earth and out of the other side unchanged. (About a 1% attenuation in 1 TeV neutrinos as they pass through earth is expected. This absorp-

tion can be used to geophysically probe the earth.)

Information Capacity

Thus, the intrinsic bit handling capacity of the existing accelerator is 53.1 MHz. The accelerator can unload the entire contents of circulating protons in one cycle (21 μs) consisting of 1113 equally spaced buckets, each one nanosecond wide, but not all filled. It would be desirable to eject these buckets on an individual basis with a switching time faster than about 18 nanoseconds. Such a "fast" bucket kicker system would have to be developed and would use a pulsed electric or magnetic field, or coded traveling waves (as show in Figure 2 below). With such a fast bucket encoder, a message of at least (since a message could be programmed in a way utilizing the unused circulating bins from the first circulation on the second or third go-around) 1113 bits could be written at a rate of 53.1 MHz. Such a system is useful for small neutrino receivers.

The encoder can also effectively utilize long extraction periods. (A two (2) millisecond time period is now routinely used.) In this scheme, the encoder (a fast bucket kicker located after the point of extraction) would be able to code 1.1×10^5 bits/2 milliseconds. Technologically, the extraction could be extended to several seconds and a message delivery rate of 53,100,000 bits per second seems possible in principle. This scheme would be useful for large water target receivers. A 10^{11} ton water target neutrino interaction detector 2,750 km from Fermilab could detect one interaction per bucket on the average. Below we describe, in the order of simplicity, information coding techniques easily adapted to the Fermilab accelerator.

Ia. Booster Batch Pulse Encoding of the Main Ring

This is the easiest coding of the circulating protons in the main ring, also carrying lowest amount of information. It takes advantage of the property that the booster fills only 1/13 of the main ring in a fast injection time period (21/13 μs). Hence, a thirteen bit message can be encoded into the main ring simply by either filling the main ring booster batch segment of leaving it empty. Shown in Figure 3 is the circulating number 5,777 coded in the binary form. In this way numbers up to 8191 can be "batched coded" into the main ring.

Ib. Booster Batch Amplitude Encoding of the Main Ring

In addition to pulse coding, amplitude encoding is also possible, allowing for a much higher information content message. The amplitude of each batch is directly proportional to the number of protons in that batch (usually around 1.0×10^{12}). The intensity

of the protons in the linac could be code adjusted for loading of each booster batch and could thus be used to amplitude modulate each of the 13 batches. In this way a message content much higher than 13 bits is available in the booster batch coding scheme.

A sensitive underseas neutrino interaction receiver could detect amplitude variations by monitoring the number of neutrino interactions in a particular batch. The accuracy to which the amplitude can be determined is of course proportional to the square root of the number of neutrinos detected per batch segment.

II. The Second Easiest Encoding Scheme

Consists of manipulating each of the 84 buckets of protons circulating in the boster kicker encoder located in the booster VSD, or fast bucket ring or just after the transfer point from the booster ring before entry into the main ring. Booster bucket coding should take place at the lowest energy of the acceleration cycle at which protons no longer migrate from bucket to bucket.

The VSD operates on the principle that the location of a bucket can be sensed and sent along a "cord line of the booster or the main ring" to an "encoder" (located downstream in the donut) (figure 5) where the signal can be used to spoil the bucket (by negative feedback) and be in this way gradually erased from the circulating series of loaded buckets. This technique allows one to code any number up to 2^{84} (or 25 digit number) in one booster batch.

Currently, since the buckets from the FNAL linac do not match the booster bucket spacing (nor are they at any harmonic), coding via a fast linac injector does not seem possible without major facility revision. It may be possible in the future to adjust the linac rf accelerating frequency to synchronize with the initial 30 MHz booster frequency thus enabling one to code three linac buckets for one booster bucket.

The VSD allows for amplitude coding of the individual booster buckets and thereby greatly increases the information capacity of the 84 bit circulating booster pulse train.

After coding, the batch is synchronously loaded into the main ring, at an rf of 52.8 MHz, where a clock keeps track of the locations of the indexed buckets.

The remaining twelve (12) batches can be similarly coded in the booster, injected into the main ring and strung together to encode a 1113 bit message.

III. The Third Easiest Encoding Scheme

In this scheme all of the buckets in the main ring are loaded to full capacity. In the first variation the encoder would utilize the VSD of the main ring to selectively erase out (in part or completely) code selected buckets. In this way, an amplitude and digitally coded message can be written into the circulating series of buckets of the main ring. In the pure digital mode, a 1113 bit binary number (or a 335 decimal digit number) can be encoded onto the circulating beam in the main ring in a test of the communications aspect of the small target neutrino oscillations experiment, p. 561. A identical pattern can be written in the next circulating series of buckets thereby allowing a repeatable transfer of a beam to the detector site. Reinforcement of a message by repeated transfer to the receiver is possible allowing the message to be eventually read by a weak detector.

A 2 ms extraction system currently in use (which blows up the radial component of the circulating buckets to gradually withdraw the beam) will also retain the message in the transmitted neutrino beam in a weak but repeated form.

Alternatively, the VSD can be bypassed and a message written by peeling off a portion of the bucket, then, with the aid of an external encoder, leaving the ejected bucket in the beam transport or removing it with the fast bucket kicker. This allows one in principal to write a message at a rate of 53,100,000 bits/second.

In all cases it will be necessary to sense the index of the bucket (with the aid of a photomultiplier secondary emission counter and synchronized clocks) at the start of transmission for each delivery. A computer program at the detector will "reorder" the repeatable series to read the message (by a signal averaging technique) in the initial experiments.

IV. Synchronization

We begin the neutrino oscillations and neutrino communications experiment with three syncronized clocks, S, D, and T, at the neutrino source. Atomic clocks such as ones used by Carol Alley with an accuracy of one part in 10^{14} would be entirely suitable for our purposes. One clock, S, remains at the source, monitors and records the time the pulses are initiated at the accelerator. The iniation time of the fast spill and therefore the bucket index is believed measurable to an accuracy of about a nanosecond. The other two clocks, D and T, are transported to the detector site where clock D is used to record the times the interactions are detected at the array. A clock in the accelerator control room records the time the first indexed bucket is ejected. See figure 6.

A prepulse is sent by telephone or satellite and is used to turn on the recording (neutrino receiver) system by gating on the array electronics. The array electronics store the pulse height and time of arrival of the Cerenkov pulses at each of the modules beginning a few microseconds prior to the time the neutrino fast spill is initiated and ending a few microseconds after the fast spill has ended. A trajectory reconstruction program subsequently locates the origin of the interaction and thus the indexed bucket.

After a long waiting time, <u>when</u> the drift of the clocks, D and T approaches the accuracy to which the transit time of the neutrinos is to be measured, it is necessary to resynchronize the clocks. At that time, clock T is compared with clock D, then T is transported to the neutrino source, where it is measured for drift relative to S, resynchronized with S, and finally transported back to the detector, where it is compared with D and is used to resynchronize D. The measurements of the drifts T-D and T-S can be used to attain the necessary precision in the time of flight measurements.

V. Neutrino Interaction Detector

The details of detecting the neutrino interactions from the Cerenkov light produced by the secondaries are to be found in reference 2 and will not be covered here. It is necessary that module spacings be closer than about 6 meters to identify the precise bucket associated with the interaction. The number of interactions per bucket can be sensed from the amplitude of the cerenkov light or with the aid of high spacial resolution hodoscopic receivers made of wire proportional counters, magneto strictive devices or the like.

VI. Future Modifications

In the future, where a neutrino generator-detector system with high interaction rates on a per pulse basis can be constructed, a start signal consisting of a station call bin with five or ten times the intensity as others can be used to signal the initiation of the message, thereby eliminating the need for synchronization. Such a system would consider an adjustment of the linac rf accelerating system to synchronize with the booster ring frequency allowing coding at a lower beam energy where coding may also be energetically easier.

ACKNOWLEDGEMENTS

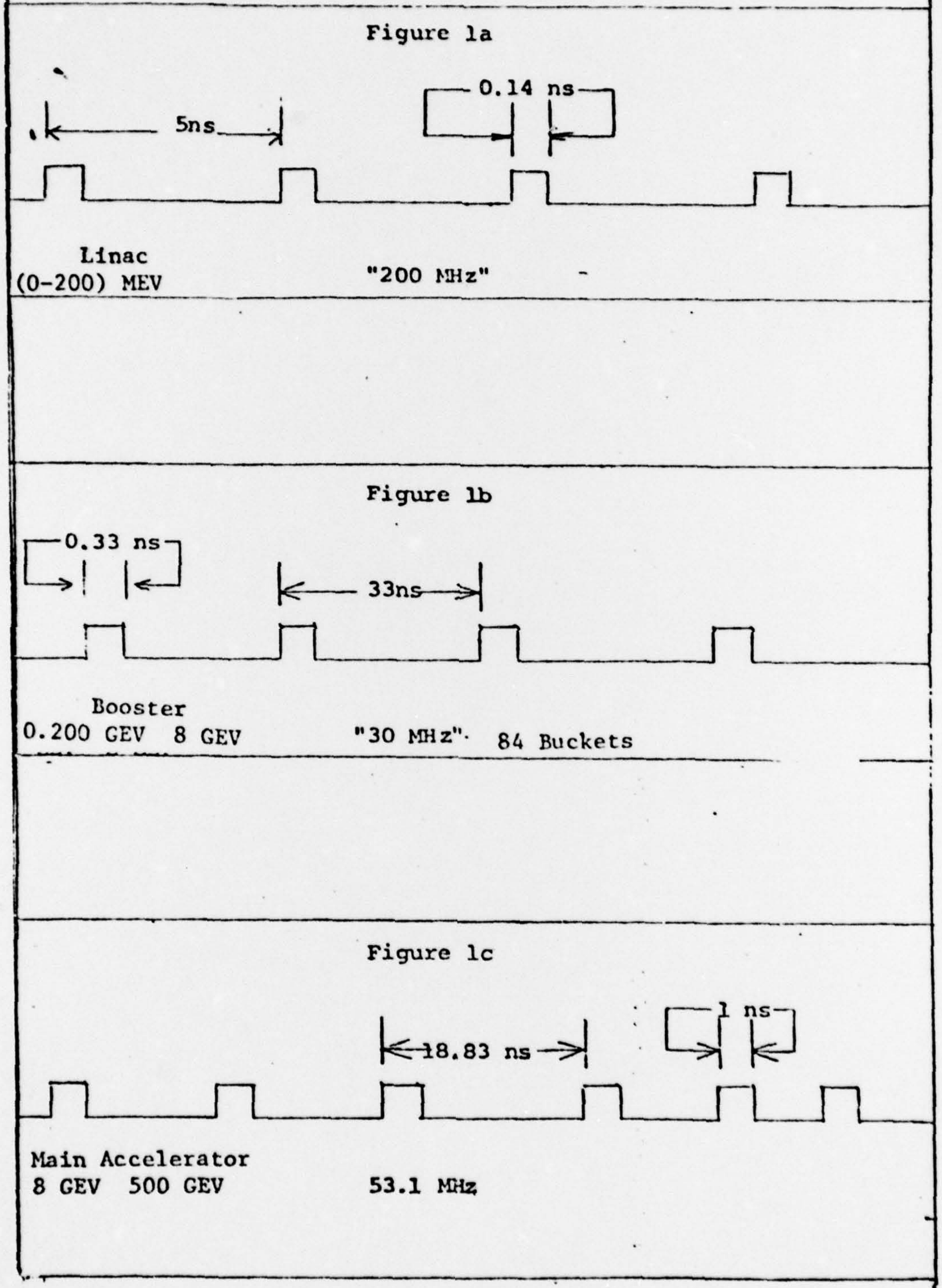
We wish to thank the entire accelerator staff for their discussions regarding the operating characteristics of the machines. We are particularly indebted to R. Davisson, Jere Lord and Seth Neddermeyer who kindly reviewed the manuscript before submission for publication.

REFERENCES

(1) "A Study of Neutrino Interactions in a Large Water Target at Great Distances from the Neutrino Source." James Albers, P. Kotzer, Seth Neddermeyer; April 1977, Fermilab Proposal 561.

(2) "Proceedings of the 1975 Summer Workshop on Neutrino Interactions in the Ocean Depths and on Oceanographic Physics and on Marine Engineering." Peter Kotzer, Editor; Western Washington State College, January 1976.

Fig. 1. BEAM FINE STRUCTURE AT THE FERMILAB



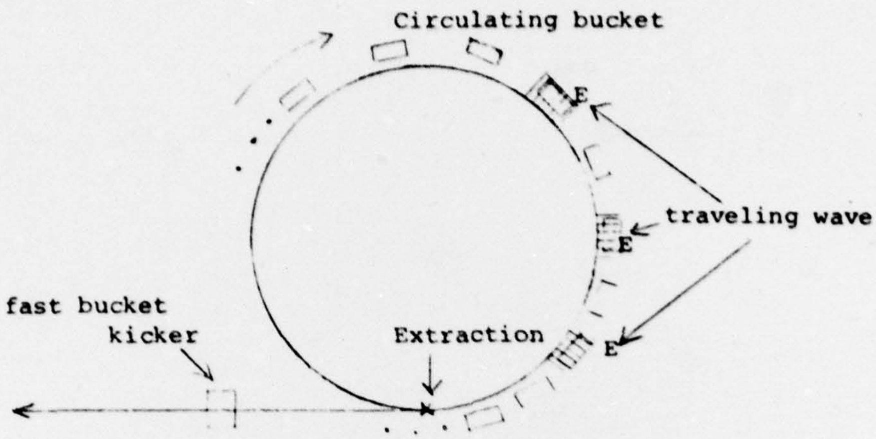


Figure (2)

"Traveling Wave" Encoder Used Either in Booster or Main Ring

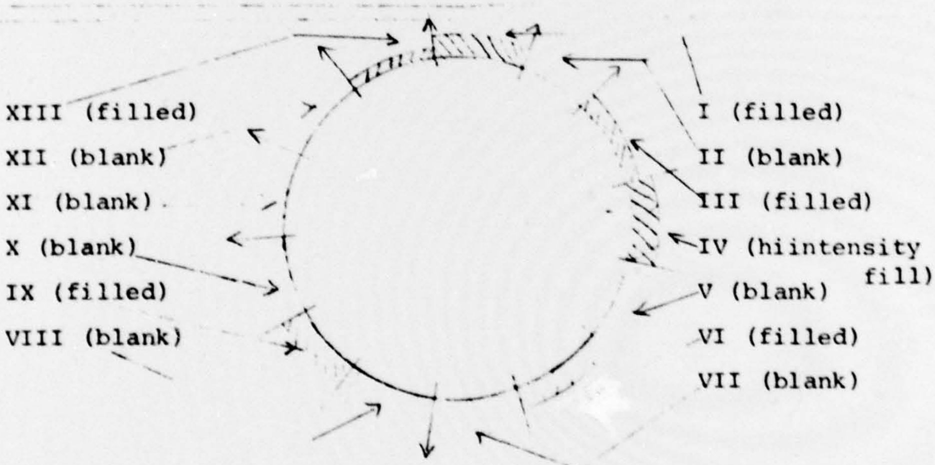


Figure (3)

Main Ring Booster Batch Coding

The thirteen circulating booster batches represent the binary number, (1011010010001) which is (5777). In addition, the intensity of each booster batch can also be varied allowing for amplitude coding of information.

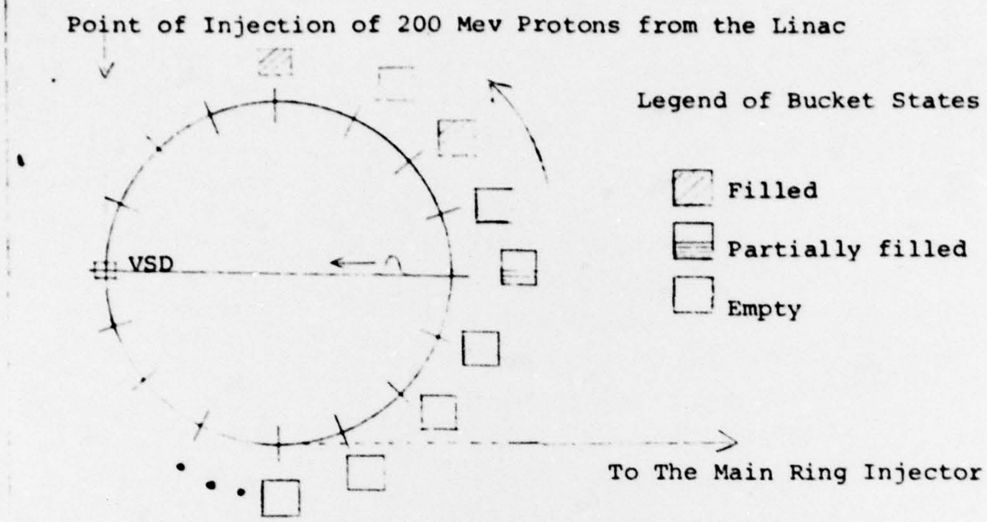


Figure (4)

(The Eight GeV Booster with 84 circulating buckets)

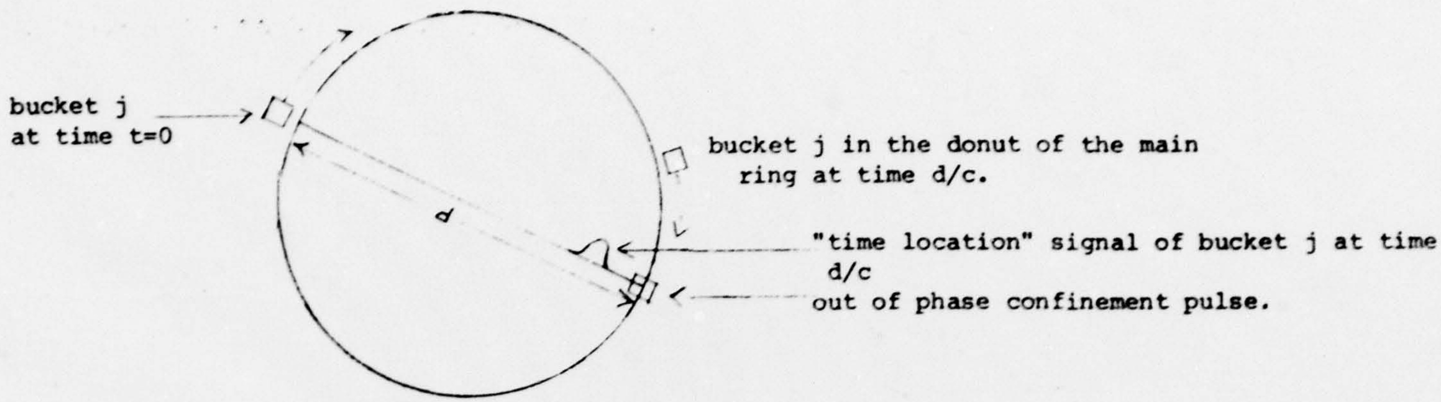


Figure 5

Vertical Super Dampe: Operation

The bucket "time location pulse" is used to provide an out of phase signal at the time bucket j reaches indicated location at the donut. The applied pulse is out of phase to the confinement pulse normally applied to bucket j at that point.

FIGURE 6

Figure 6 a

Initial Synchronization of Clocks S, D, T and A at Fermilab at t=0.

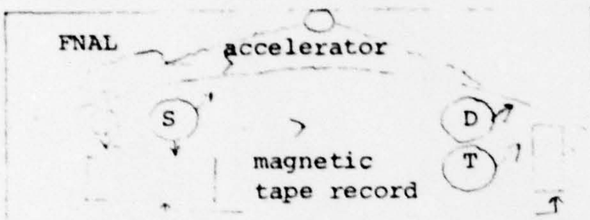


Figure 6 b

Transport of D and T to Ocean Site Array at $t=t_t$.

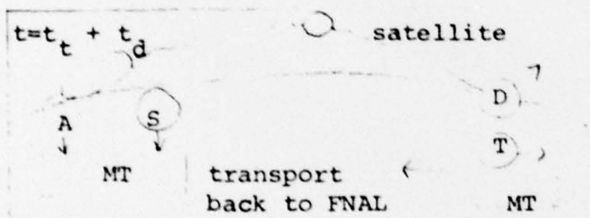


Figure 6 c

Transport of Clock T to Fermilab for resynchronization.

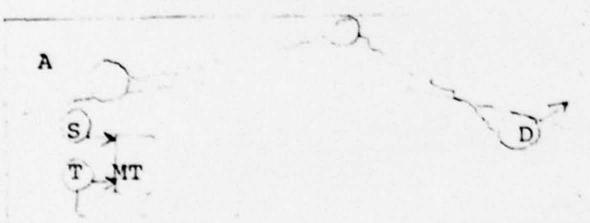


Figure 6 d

S and T are compared and time difference is recorded. Then T is reset and transported back to detector site.

Figure 6 e

Comparison of T with clock D and synchronize D to clock T.

TIME SYNCHRONIZATION SYSTEM